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Narrowband measurements of polarization-mode dispersion using the modulation phase shift technique

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A common characteristic of the current methods for measuring polarization-mode dispersion (PMD) is the need for a broad optical bandwidth. With the increasing use of wavelength division multiplexing the need to make PMD measurements within a very narrow optical bandpass will also increase. One technique which is well suited to narrowband measurements of PMD is the modulation phase shift technique (MPS). While the concept is not new [1-4], we believe the work here to be the first published demonstration of the accuracy of the technique in measuring differential group delay (DGD) vs. wavelength.

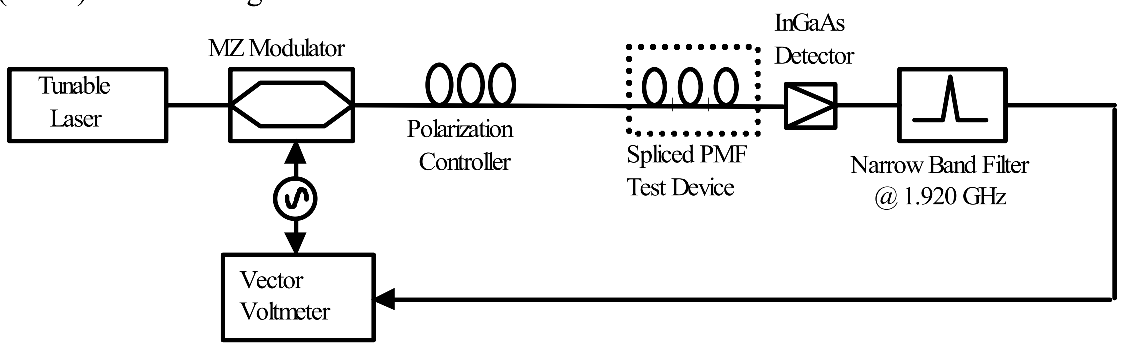

Figure 1 Schematic diagram of modulation phase shift system for DGD measurement.

The MPS technique is well known for its use in chromatic dispersion measurements [5]. The basic principle is to directly measure the group delay of light traveling through each of the two principal states of polarization of the device under test. The experimental setup is shown in Figure 1. The light from a tunable laser diode with an RF-broadened linewidth of 50-500 MHz undergoes an external 1.920 GHz intensity modulation from a $LiNbO_3$ Mach-Zender modulator. The modulated light passes through a polarization controller, passes through the device under test, and is detected with a high-speed InGaAs photodetector and filtered with a narrowband filter at 1.920 GHz. A vector voltmeter is used to measure the phase between the RF electrical modulation signal and the optical signal out of the device under test. The phase is a measurement of the group delay through the optical system, so adjusting the polarization controller to maximize the optical phase delay means that the light is being launched down the slow principal axis of the device under test. Likewise, the polarization orientation for minimum phase delay corresponds to a launch down the fast principal axis. The difference in phase between these two launch conditions is a measure of the DGD at the wavelength under test. That is, DGD ($\Delta\tau$) is given by

$$\Delta\tau = \frac{\varphi_+ - \varphi_-}{360° \cdot f}, \tag{1}$$

where $\Delta\tau$ is in seconds, φ_+ and φ_- are the measured phases (in degrees) for the transmission along the slow and fast axes respectively, and $f = 1.920\times10^9$ Hz.

In order to demonstrate the accuracy of this technique, we made a measurement on three concatenated segments of bow-tie polarization-maintaining fiber (PMF) oriented at roughly 45° angles so as to mix polarization modes, providing a DGD with a strong wavelength dependence. The maximum DGD of the PMF concatenation is about 8 ps. The vector voltmeter used in this measurement has a phase resolution of 0.1° which at 1.920 GHz corresponds to a time resolution of 0.145 ps. A 360° phase change would represent a 520 ps delay. Therefore, given the PMD of the device being measured, there is no danger of a 2π phase ambiguity. Using the MPS technique, we measured the DGD of the PMF device over about a 20 nm range and compare the results with DGD-vs.-wavelength measured by the more conventional Jones matrix eigenanalysis (JME) method [6]. Measurement results for the two techniques are compared in Figure 2.

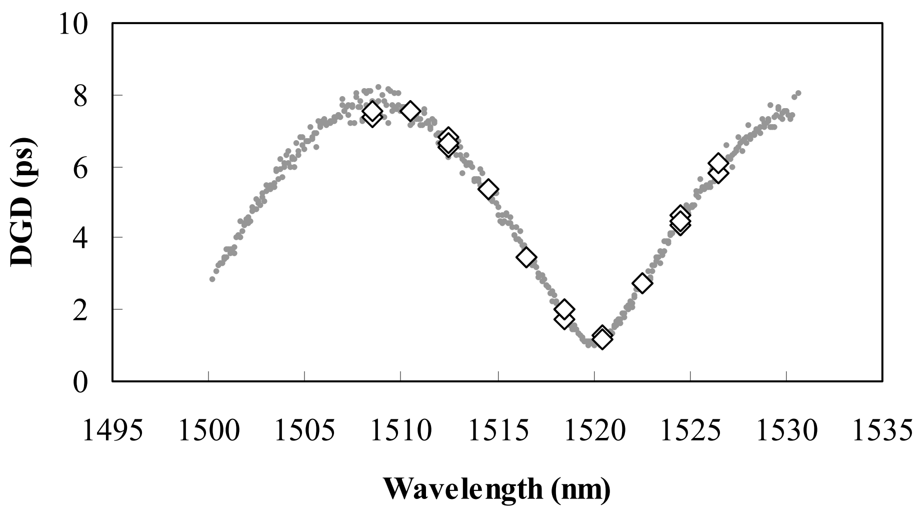

Figure 2 DGD vs Wavelength for JME technique (dots) and MPS technique (diamonds) on a three-section PM fiber.

It should be noted that the JME measurements were made at a temperature ~3 °C lower than the MPS measurements. The temperature dependence of the birefringence (Δn) of PMF $d(\Delta n)/dT$ is on the order of -4×10^{-7}/°C [7]. This means that for a single section of PMF, a few degrees of temperature change will affect the DGD by only a few tenths of one percent. However, a change in the birefringence of the fiber sections also changes the mode-coupling conditions. This effect depends on the retardance of the sections, which is proportional to $\Delta nL/\lambda$ (where L is the length of the PMF section and λ is the optical wavelength). From this relationship, we see that a change in ΔnL will be equivalent to a change in λ (wavelength shift). Multiple measurements of the PMF test device using the

JME system showed an effective wavelength shift with temperature of –0.8 nm/°C. We therefore anticipate that the data taken at the lower temperature (JME) would be offset by about 2-3 nm. The agreement between the JME and MPS data is good when we shift the JME data down by 2.5 nm. This value gives the best fit and corresponds well to a 3 °C temperature shift. Consequently, the JME data shown in Figure 2 have been shifted by 2.5 nm.

The uncertainty in the MPS measurement comes primarily from two sources: phase uncertainty due to the resolution of our vector voltmeter and the degree to which we were able to launch exactly on the principal axes. Fabry-Perot effects in the measurement system are significantly reduced by RF-broadening the source, and the residual random phase uncertainty is completely explained by the 0.1° phase uncertainty of the vector voltmeter. The uncertainty due to launching nonprincipal states is a source of systematic error. The measured phase difference between two orthogonal launch states is a function of the alignment of the launch states with respect to the principal axes. Figure 3 shows the fractional DGD error encountered for a given alignment error. Alignment error is the angle (on the Poincare sphere) between the launch polarization state and the slow principal axis of the device under test. Any misalignment error therefore causes a reduction in the measured DGD. Fortunately, the error is a weak function of misalignment for small angular errors. For example, a 5° misalignment angle will yield a measured DGD which is only 0.4% below the true value.

We found the principal state by merely manipulating the polarization controller by hand and watching for the maximum and minimum phase delays. Repeated measurements showed that the measured phase differences for repeated runs differed by no more than 0.2° (consistent with the phase resolution of the system). Figure 2 shows that the JME and MPS techniques agree within the measurement noise. Therefore, our technique of finding fast and slow axes by hand appears to be accurate (but tedious).

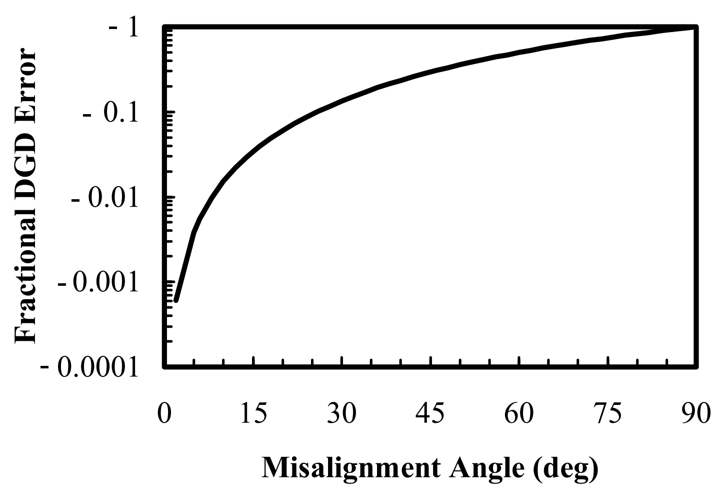

Figure 3 Fractional DGD measurement error as a function of launch state orientation (0° is ideal launch along principal states, 90° is worst-case misalignment).

In order to reduce measurement noise and add some degree of automation, we are experimenting with a differential phase (DP) measurement technique [1]. For the DP measurement, we use a commercial chromatic dispersion test system and an electronically controlled three-stage polarization controller. The first stage (a half-wave plate) is used to toggle between orthogonal states of polarization at a rate of tens of Hertz. The other two stages are used to search for the principal states of the device under test. Preliminary results predict an improved DGD resolution with a much narrower 200 MHz bandwidth requirement.

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